Star formation sustained by gas accretion at all redshifts

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Outline

- Framework and Background
- Analytical description of gas accretion
- Expected properties of the accreted gas
- Accretion inferred from gas observations (HI and HII)
- Accretion inferred from stellar observations
- Scaling laws as evidence for accretion
- Gas accretion and star formation at high-z
- Summary: take-home message(s)

Background

Cosmological numerical simulations of galaxy formation predict that accretion of metal-poor gas from the cosmic web fuels the star formation of disk galaxies (e.g., Dekel & Birnboim06, Dekel+09, Silk & Mamon12, Genel+12 ...)

This process occurs at all redshifts, when the physical conditions are given, this gas accretion occur though a particularly fast via called cold-flow accretion: the Dark Matter halo mass has to be below a threshold, typically, of the order of

$$M_{halo} \leq 10^{12} M_{\Theta}$$

The importance of gas infall is as clear from numerical simulation as it has being difficult to prove observationally. There are many hints pointing in the direction, but no final prove given yet.

Illustris:

Vogelsberger +14a,b

stellar light (top left), gas density (top right), gas temperature (bottom left), gas metallicity (bottom right).

Framework

◇ Review, so, very little self citation

◇ The presentation refers to isolated disk galaxies, i.e., it does not refers galaxies in dense environments (in clusters at redshift zero), and it also ignores satellite galaxies, where tidal forces play a key role too

◇ (Major-)mergers are unimportant for stellar mass growth, e.g.,

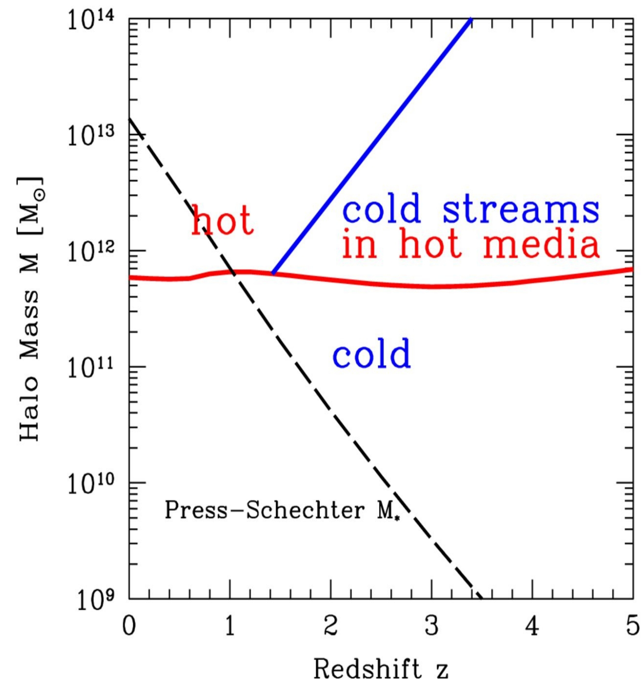
- 20% in the Aquarius simulations (Wang+11)

- 23 % in the multi-zoom simulation by L'Huillier+12

Two modes of gas accretion: hot and cold

When cosmic web gas falls into the potential well of the DM halo, it accelerates until and shocks.

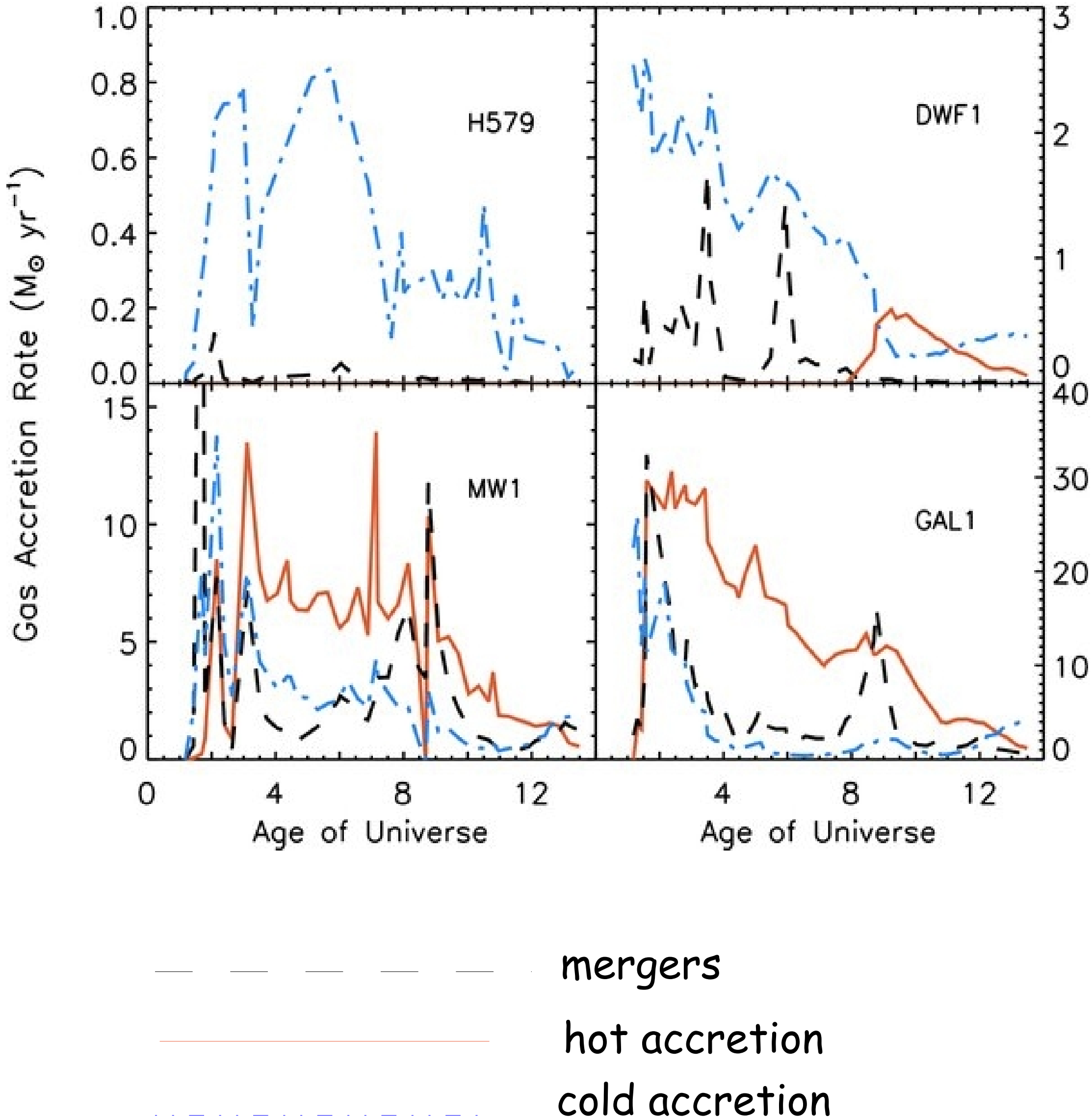
When the post-shock temperature is low enough, the cooling time is so short that the gas cools down and the shock cannot be maintained: cold-flow accretion (Birnboim & Dekel 03)



The cold flow mode provides fresh gas directly from the cosmic web and ready to form stars.

Important for $M_{halo} \leq 10^{12} M_\Theta$

- all galax at high redshift
- sub MW galaxies in the local universe



Accretion is clumpy

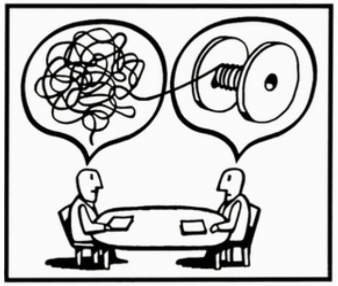
The galaxy mass increases from top to bottom and left to right

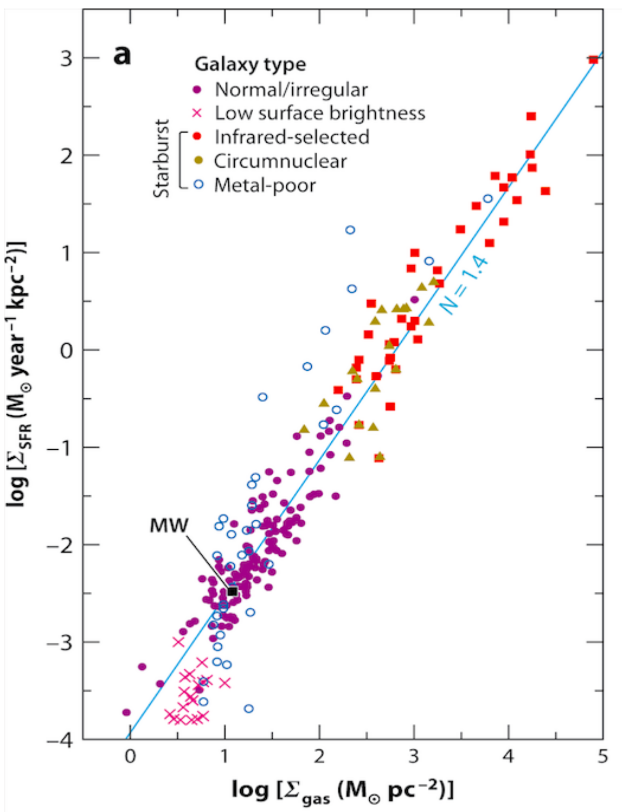
z=0

from Brooks+09

The gas accretion rate determines the star formation rate

Simple analytical model that provides physical insight





Kennicutt RC Jr, Evans NJ II. 2012.

The reason can be pinned down to the Kennicutt-Schmidt (KS)-like law

$$SFR = \epsilon M_g = \frac{M_g}{\tau_g}.$$

The star formation rate (SFR) is proportional to the mass of gas available to form stars, with a (gas consumption) time scale smaller than the rest of the important timescale,

$$\tau_g < 1\,\mathrm{Gyr}$$

... and decreases with increasing z

gas is "instantaneously" transformed into stars

$$\frac{dM_g}{dt} \equiv \dot{M}_g = -(1-R)\,\mathrm{SFR} + \dot{M}_{in} - \dot{M}_{out},$$ ← mass conservation

R return fraction

$\dot{M}_{in}$ ← gas infall rate - the driver of the system

$$\mathrm{SFR} = \epsilon\, M_g = \frac{M_g}{\tau_g}.$$ ← KS law

$$\dot{M}_{out}(t) = w\,\mathrm{SFR}(t),$$ ← gas outflow rate

w mass loading factor

Then →
$$\mathrm{SFR}(t) = \mathrm{SFR}(0)\,e^{-t/\tau_{in}} + \int_0^t \dot{M}_{in}(t')\,e^{-(t-t')/\tau_{in}}\,dt'/\tau_g,$$

$$\tau_{in} = \tau_g\,/(1-R+w).$$

Since τ_g is very small $\dot{M}_{in}$ can be pulled out of the integral and

$$\mathrm{SFR}(t) \simeq (1-R+w)^{-1}\,\dot{M}_{in}(t),$$

SFR is set the infall rate only (corrected by outflows)

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$$\mathrm{M_g}(t) \simeq \tau_{\mathrm{g}}\,\mathrm{SFR}(t) \simeq \frac{\tau_{\mathrm{g}}}{1-R+w}\,\dot{\mathrm{M}}_{\mathrm{in}}(t).$$

The mass of gas is set by infall rate: is just needed to maintain the SFR given by the infall rate

$$\frac{\mathrm{SFR_{gf}}}{\mathrm{SFR}} \simeq \frac{1-R+w}{1+w}. \qquad \frac{\mathrm{SFR_{gf}}}{\mathrm{SFR}} \simeq 1$$

The fraction of star formation produced by fresh gas (fg) is very large

$$Z \simeq Z_i + y\,(1-R)/(1-R+w).$$

The metallicity *Z* of the gas in a galaxy is independent of time, SFR and infall rate !!!

It is set only by **stellar physics** (the yield *y*, and the return fraction *R*) and by **gas outflows** (through the mass loading factor *w*).
Z_i stands for the metallicity of the infalling gas

Since *Z* varies from galaxy to galaxy, and *y*, *R* are set, w >> 1

Expected properties of the accreted gas

- low temperatures (T < 50000 K; to keep the Hydrogen neutral). Depending on the DM halo mass, mixed with hot gas ($T > 10^6$ K).

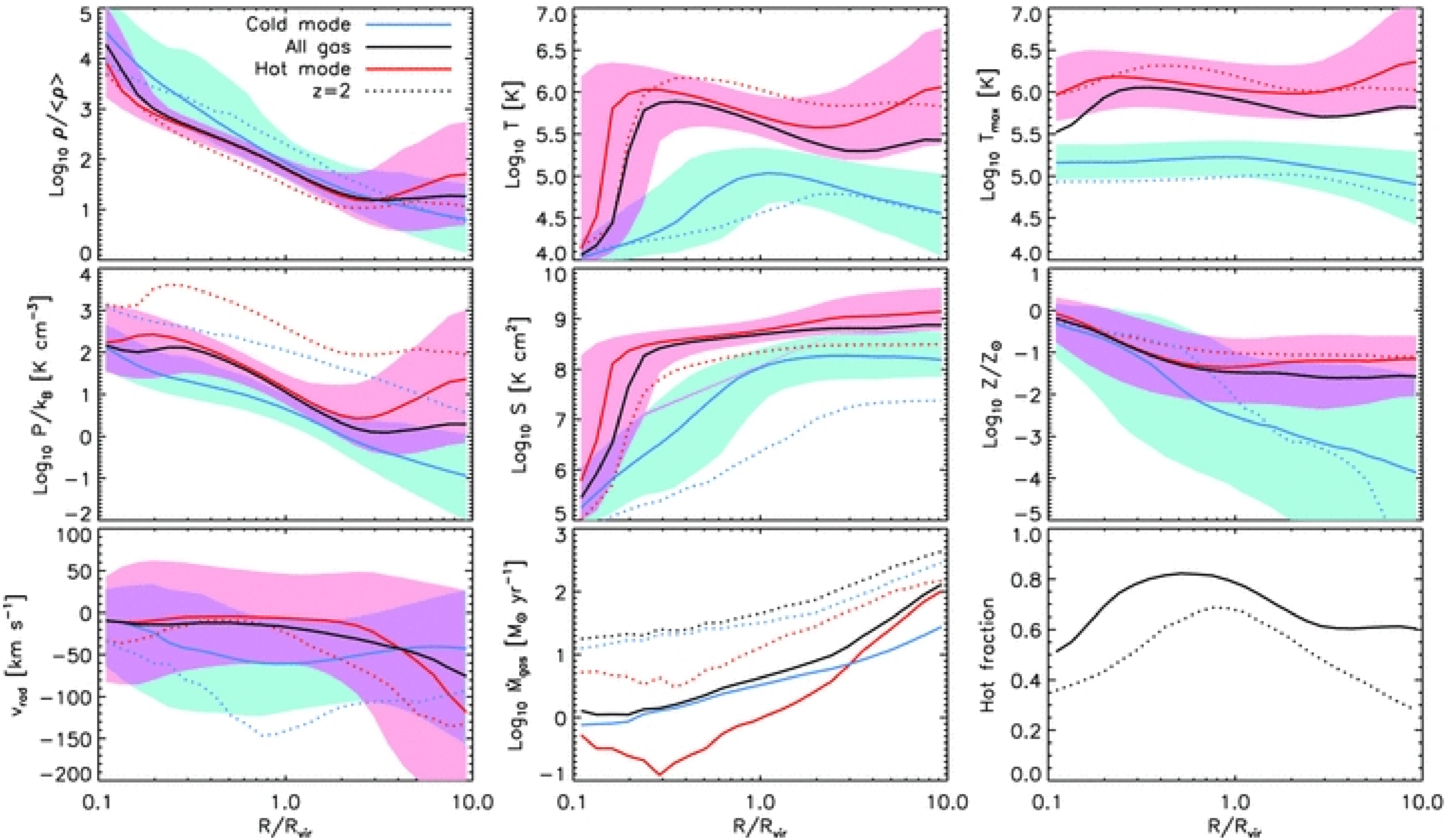
- gas infall (but infall and outflows extremely difficult to distinguish), expected to occur in the plane of the galaxy

- low metallicity (it is gas from the cosmic web gas). Due to the gas outflows, the metallicity of the accreted gas increases with decreasing redshift (becoming ~1% $Z_{\odot}$ at redshift zero).

- Lya forest. Produce absorption features in the spectrum of background sources typically QSO, starburst galaxies, or even GRB

- emission in Lya. The cosmic web gas is an ionized plasma undergoing recombination, and light scattering ... so it should produce an emission spectrum

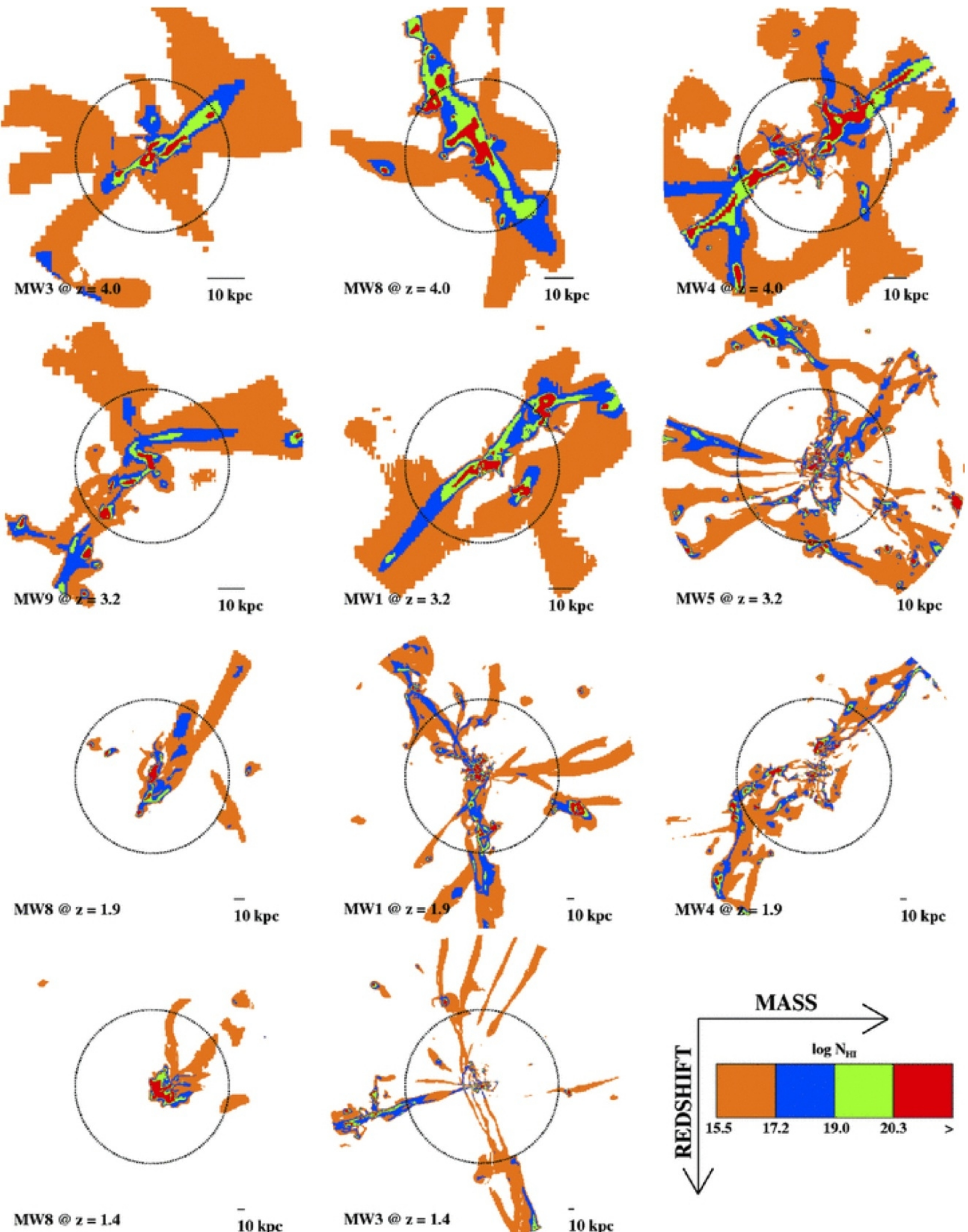
- mixed with metal rich outflows ... due to stella winds, SNe and AGN feedback. Expected to be concentrated in the direction perpendicular to the galaxy disk.



van de Voort & Schaye 12   MW-like haloes at z=0

R_{vir} is the virial radius, much larger than the optical radious (70 times larger than the half-light radius; Kartsov 13)

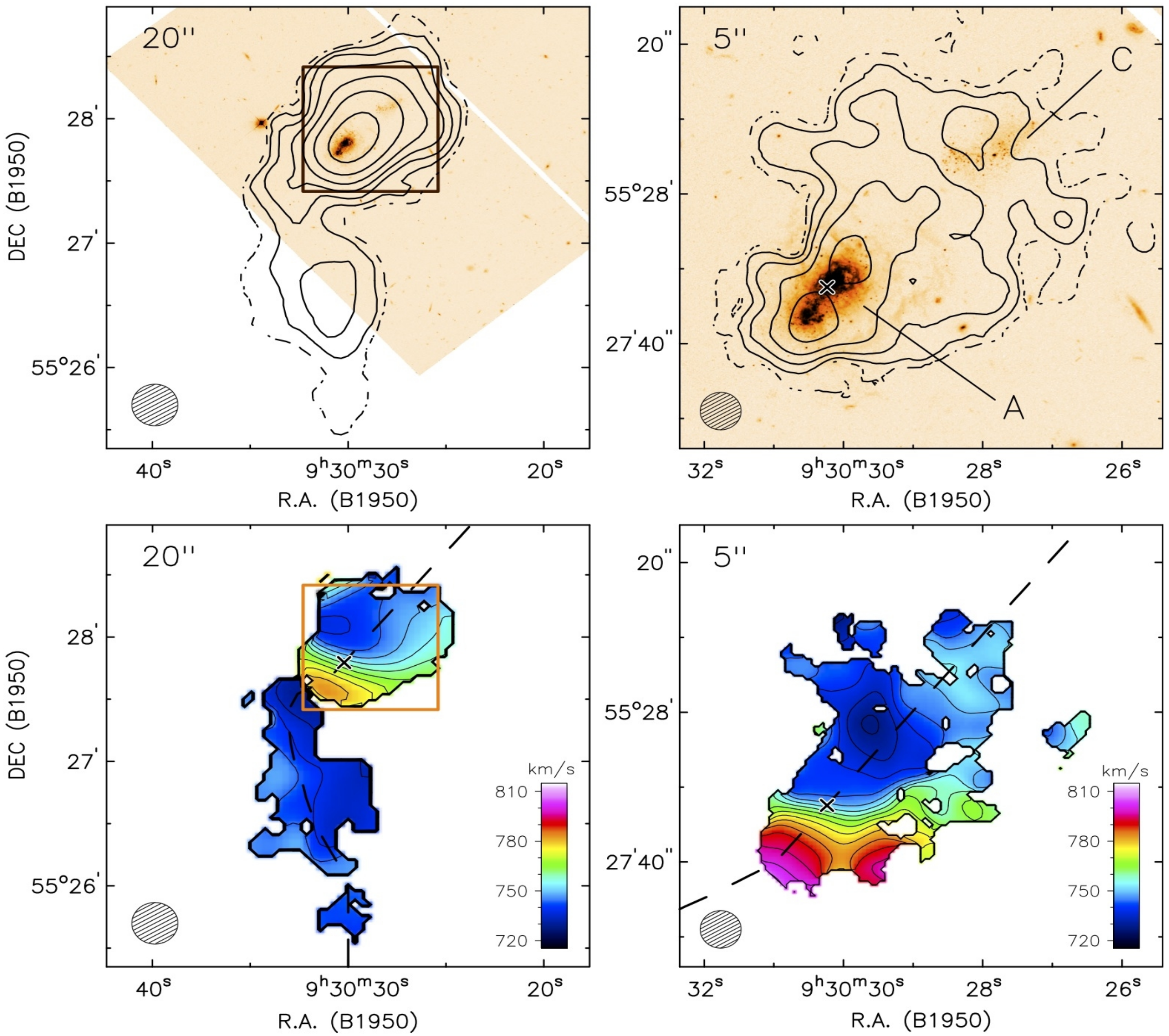
Lys systems: model predictions by Fumagalli+11



Damped Lyman Alpha absorbers (DLAs) have $N_{HI} > 10^{20}$ cm^{-2}

Lyman Limit Systems (LLS) have $N_{HI} > 10^{17}$ cm^{-2}

Accretion inferred from HI obserations



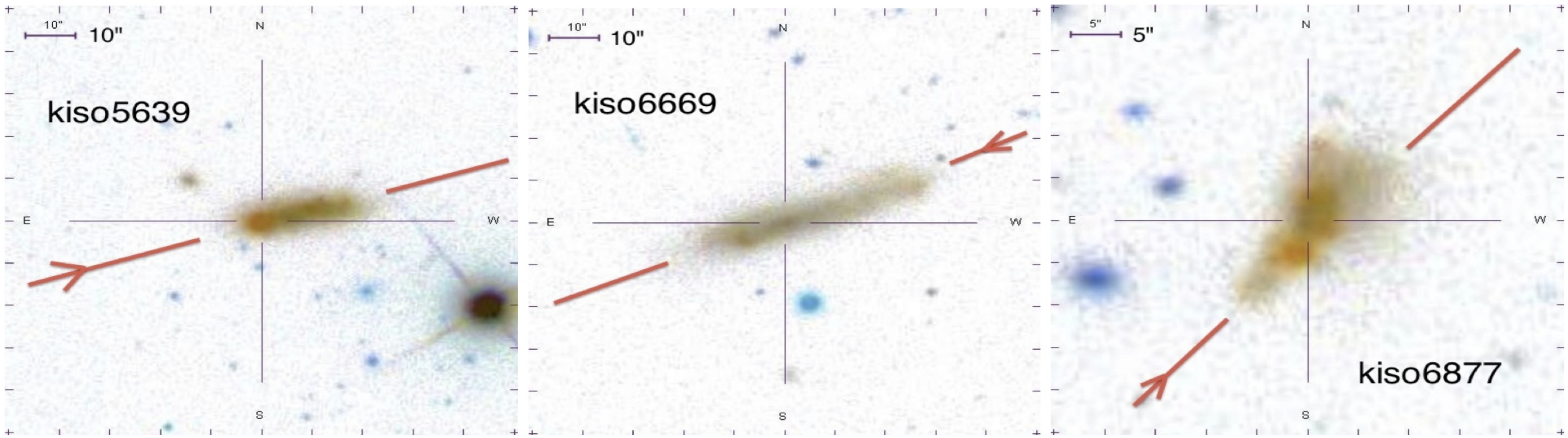
Star forming galaxies all have pools of neutral gas often with very suggestive, as the case of the extremely metal poor (XMP) IZw18

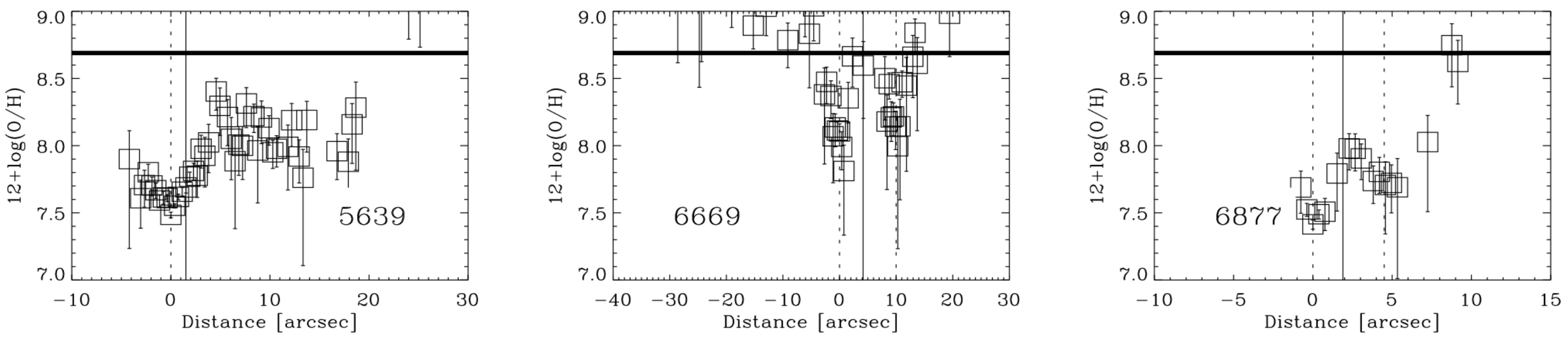
Lelli+12a

Accretion inferred from HII observations

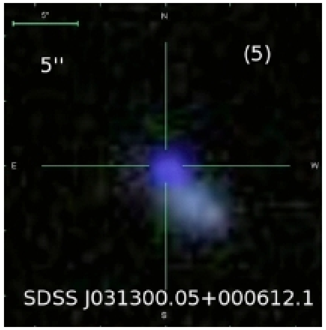
- Extremely metal poor galaxies ($Z < Z_\odot/10$) tend to be cometary (MoralesLuis+11)

- XMPs present metallicity inhomogeneities so that the larger the SFR the more metal poor (SA+13)





Local **Tadpoles-cometary-XMP** galaxies:



- the heads are giant star-forming regions

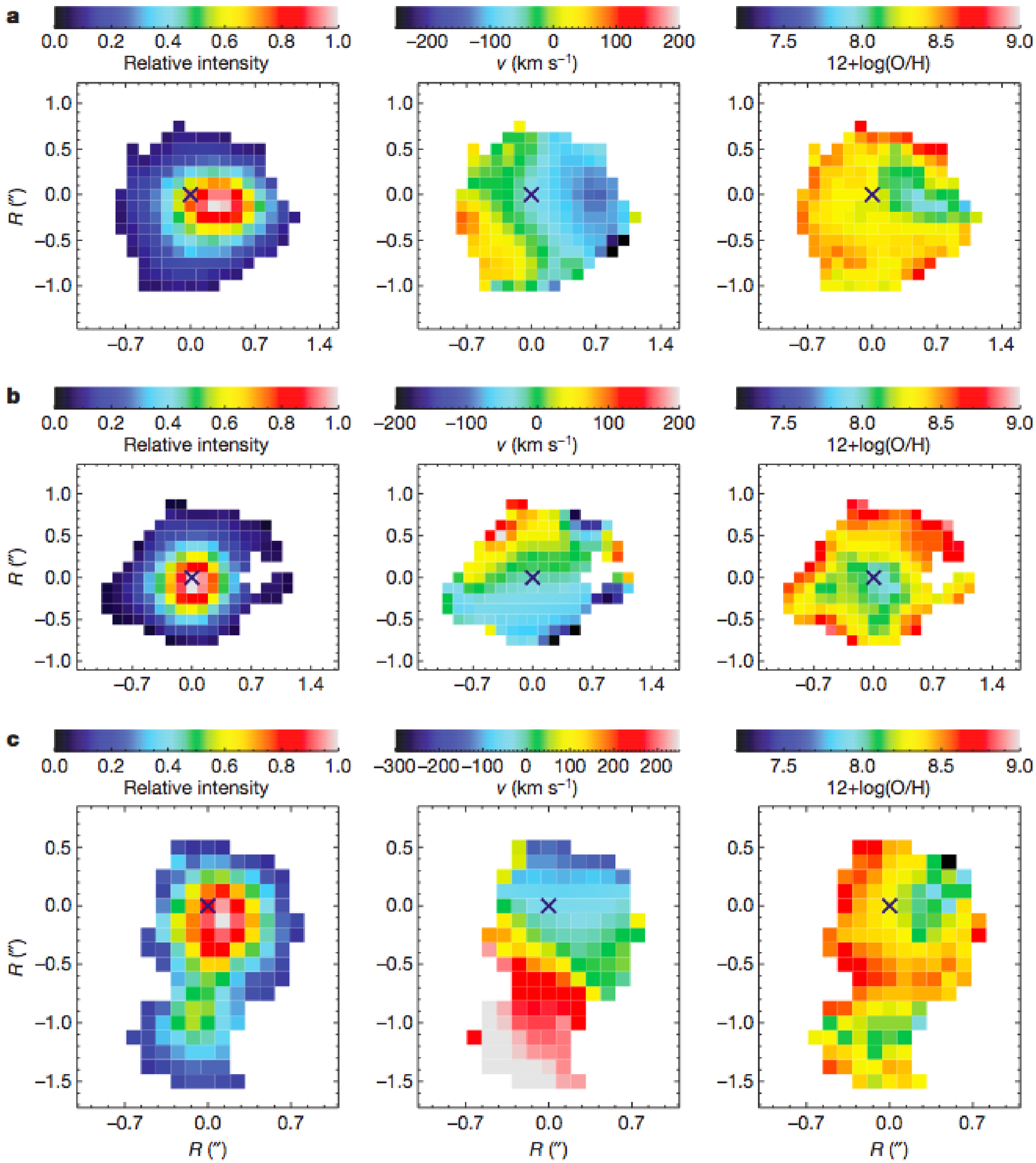
- rotate, with the heads displaced with respect to the rotation centers

- the head has a lower metallicity than the rest of the galaxy, which must be a short lived phase (ISM mixing in 100 Myr)

These observations are consistent with the heads being a star-formation episode triggered by the recent and localized inflow of pristine gas

↓

We are witnessing a cold-flow accretion episode



Evidence for cold-flows at high redshift

Cresci et al., Nat. 2010,

z	$\log(M_*/M_\odot)$
3.065	$10.68^{+0.16}_{-0.54}$
3.219	$10.03^{+0.40}_{-0.08}$
3.288	$10.86^{+0.18}_{-0.41}$

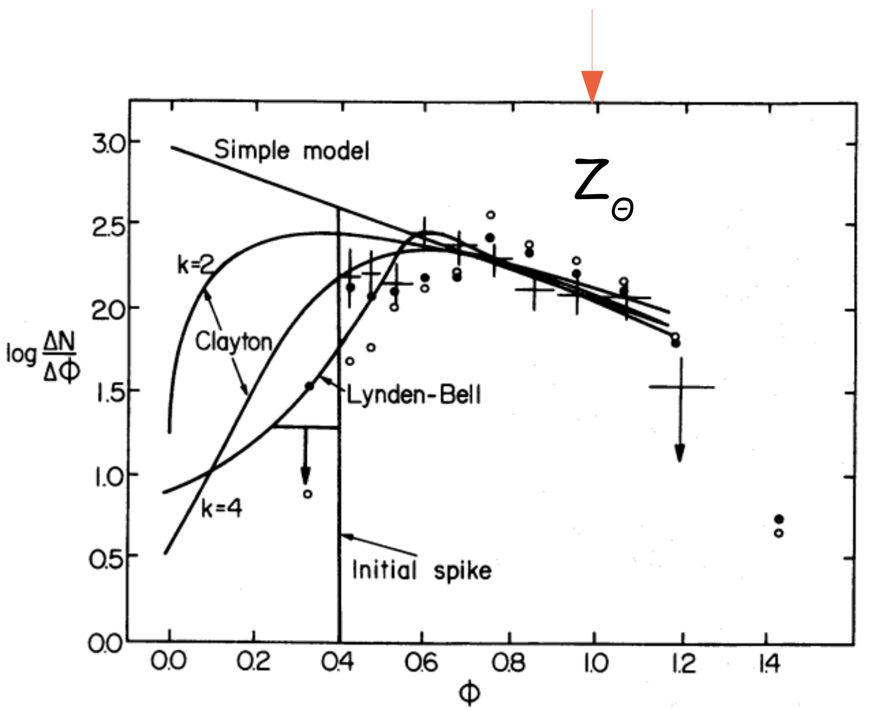
Accretion inferred from stellar observations

Often the morphology of the galaxies as observed in broad band (thus tracing stars) is distorted with signs of recent accretions of large amounts of gas in a single episode.

The polar ring galaxies are extreme cases (e.g., Combes+13)

The G-dwarf problem

There is a notorious deficit of sub-solar metallicity G-dwarf stars in the solar neighborhood (van den Berg 62; Schmidt 63), as compared with the distribution expected in closed-box evolution where every new population is less numerous than the preceding one.



Φ is metallicity in linear scale

(from Rocha-Pinto & Maciel 96)

The deficit is actually and excess of G-dwarfs with solar metallicity, easy to explain in the stationary state gas infall model (Larson 72)

$$Z \simeq Z_i + y\,(1-R)/(1-R+w).$$

$$y \approx Z_\Theta$$

The same deficit occurs in other galaxies as well (Worthey+96)

Scaling laws as evidence for accretion

A number of observational properties characterizing large samples of star-forming galaxies can be explained if the star formation is driven by metal poor gas accretion.

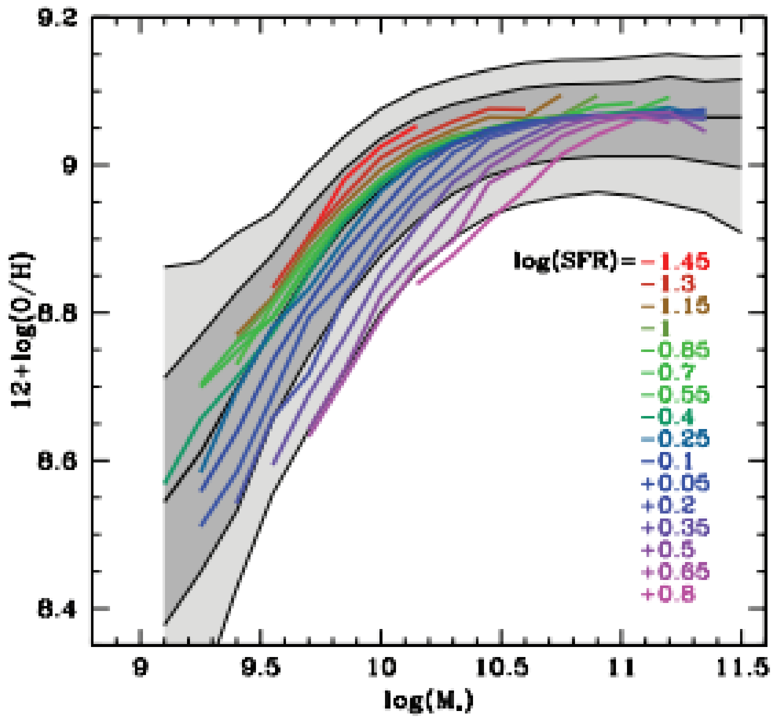
... the underlying physical mechanism has to be something fundamental since it affects not just a few objects but the bulk of the star-formation galaxies

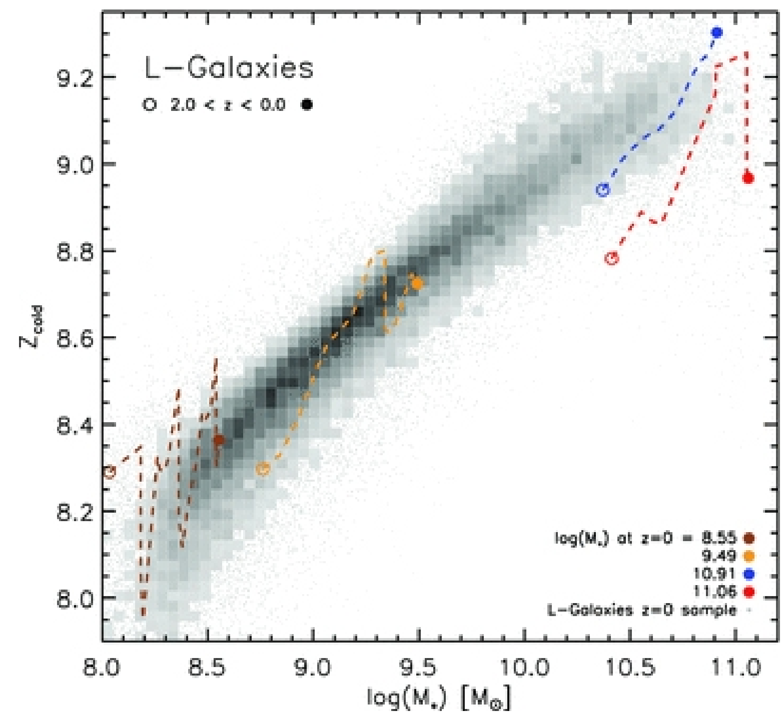
- short gas consumption time-scale compared with the age of the stars
- the large metallicity of the quiescent BCDs
- metallicity morphology relationship
- stellar mass-metallicity-gas mass relationship
- stellar mass-metallicity-size relationship
- stellar mass-metallicity-SFR relationship, i.e., the so-called Fundamental Metallicity Relationship

Fundamental Metallicity Relationship

Given a galaxy mass, the metallicity decreases as the star-formation increases

Mannucci+10; Lara-Lopez+10





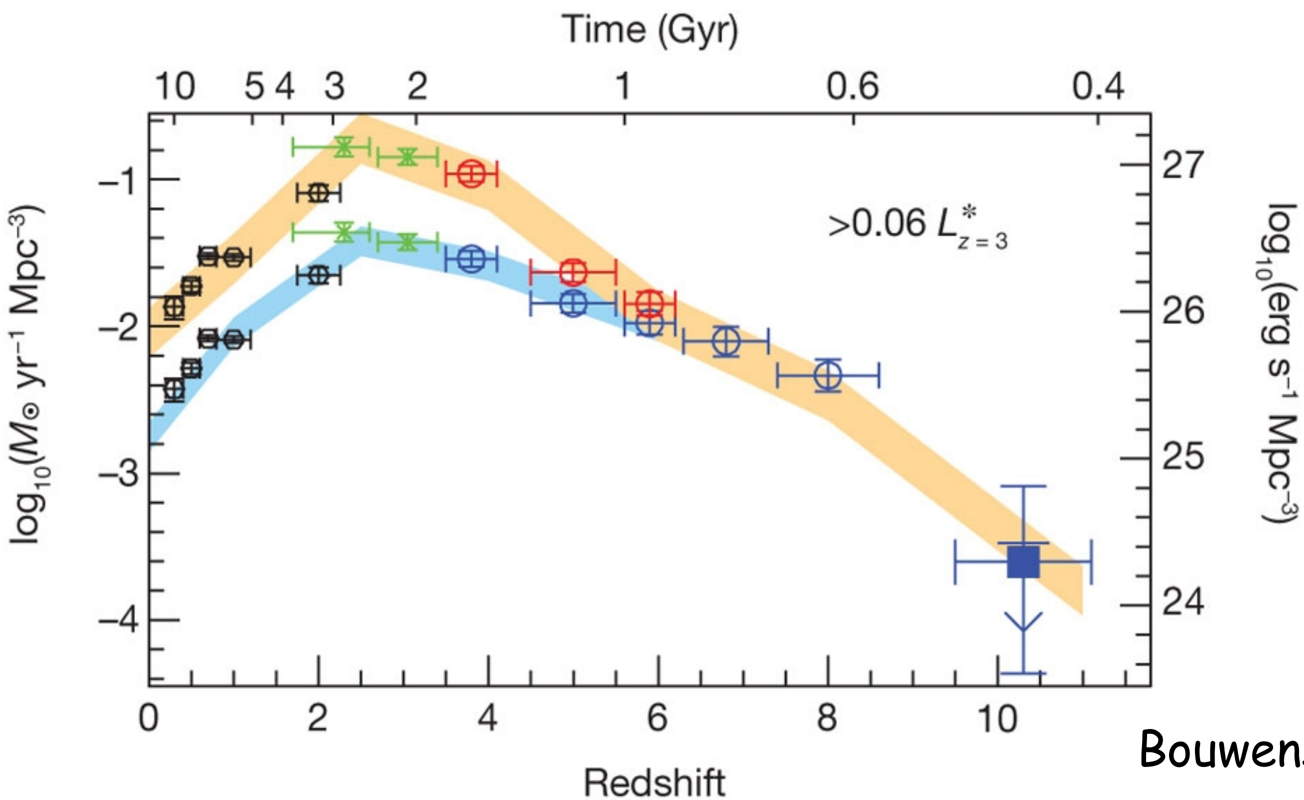
Yates+12 (semi-analytical model)

Easy to interpret if the starburst is triggered by pristine gas inflow

Gas accretion and star formation at high redshift

Star Formation history of the universe

Madau-Lilly plot



Bouwens+11

The observed variation with z of the SFR of the universe just reflects the gas accretion rate onto individual galaxies

(from Dekel+13)

$$\dot{M}_{in} = f_b \, f_{gal} \, \frac{dM_{halo}}{dt}.$$

$$\frac{dM_{halo}}{dt} \approx 30 \, M_{halo,12}{}^{1.14} (1+z)^{2.5} \; M_\odot \, yr^{-1},$$

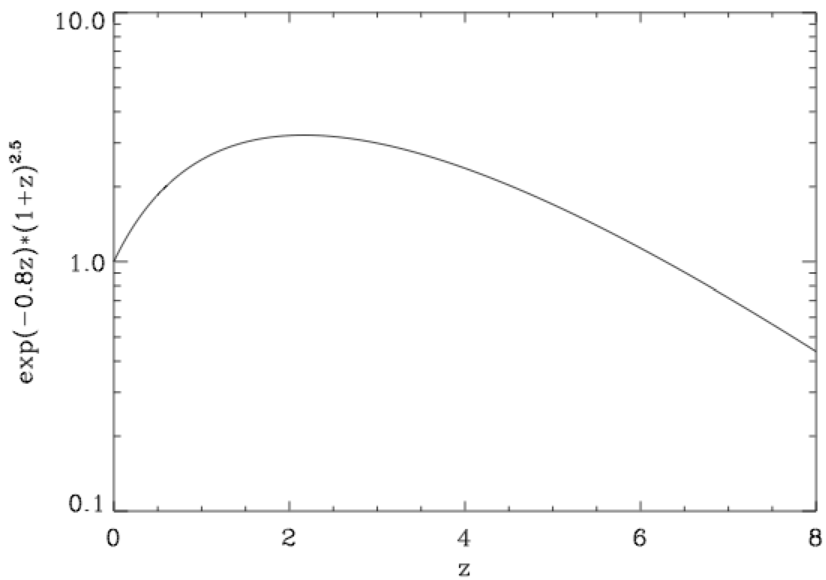
$$M_{halo,12} \approx M_{halo,12,0} \, e^{-0.79(z-z_0)} \, ,$$

$$\frac{dM_{halo}}{dt} \approx 30 \, M_{halo,12,0} \, e^{-0.79(z-z_0)} (1+z)^{2.5}.$$

f_b is the cosmic baryon fraction

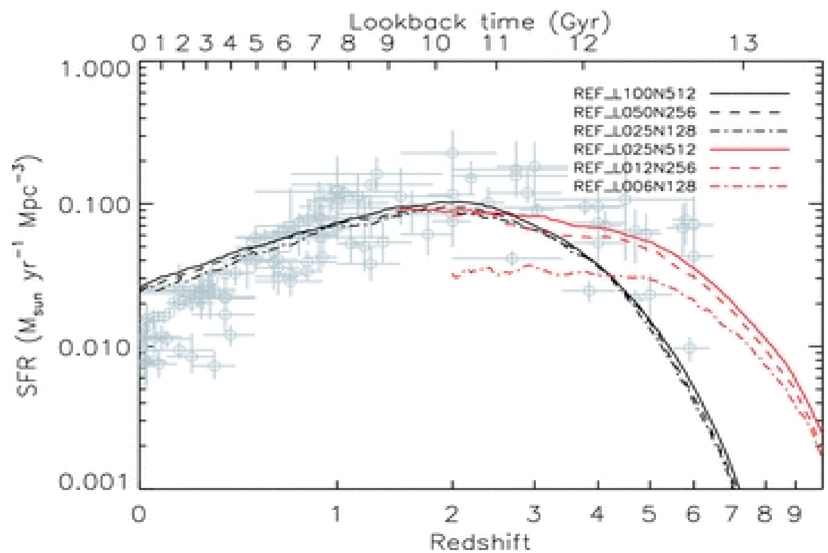
f_{gal} is the fraction that reaches the galax

$$y = \exp(-0.79 \, z) \cdot (1+z)^{2.5}$$



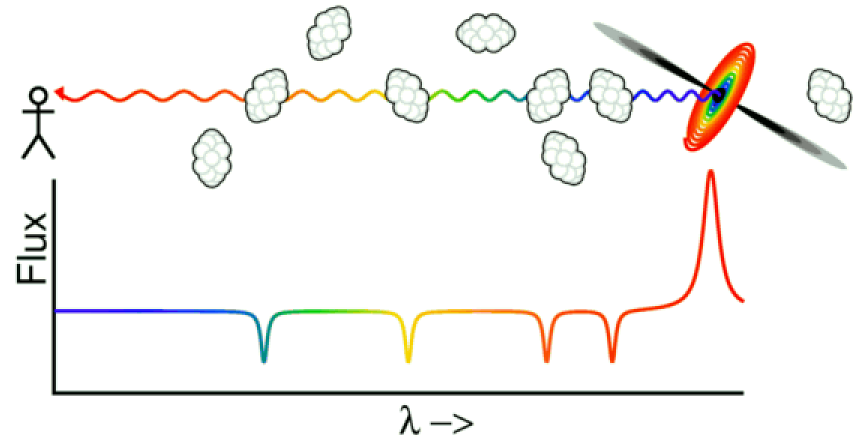
If you do it properly

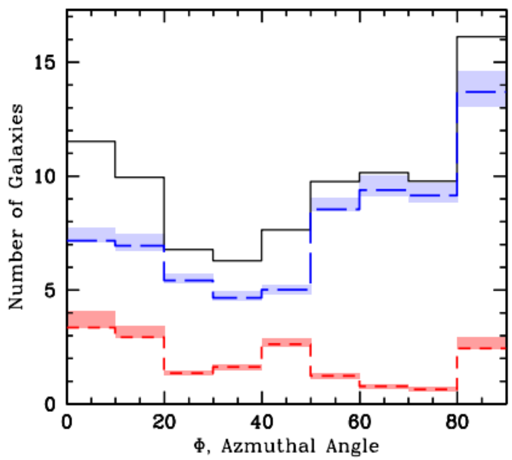
Schaye,Dalla Vecchia+10



The cosmic web in absorption

(multi-phase) gas absorption observed on the spectrum of a background source, typically a QSO

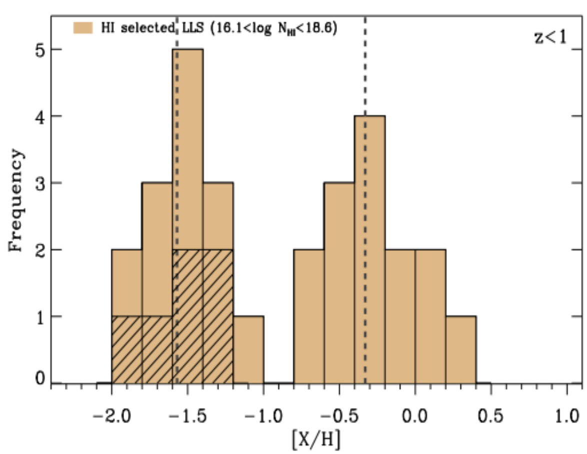




The MgII absorption occur perferentially at 0° and 90° (Kacprzak+12)

0°

90°



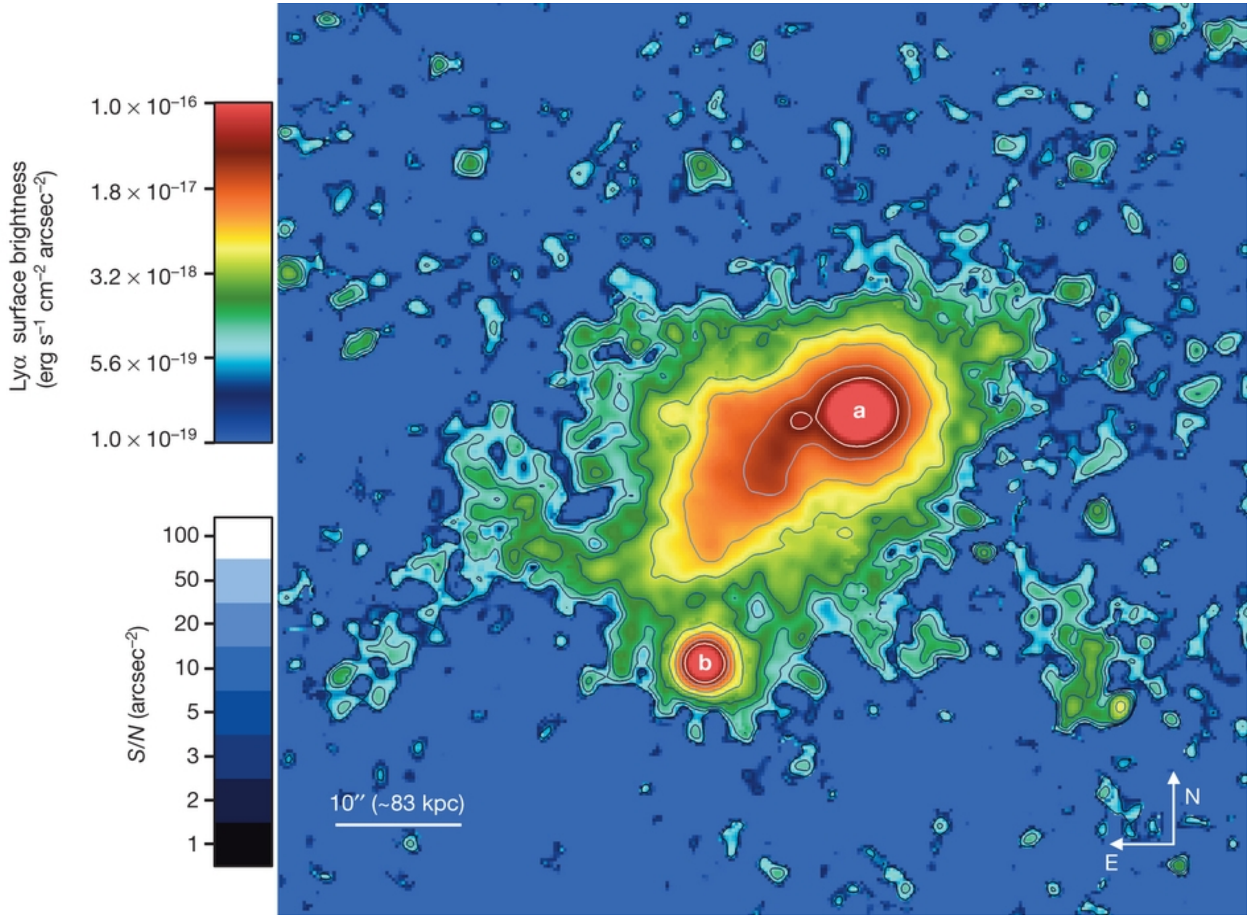
The metallicity distribution of MgII absorption is bimodal, $Z_{\odot}$ and 3%$Z_{\odot}$, (Lehner+13). z < 1

The two components represent inflows and outflows

The cosmic web in emission

Lya emission that extends further out of the virial radius of the galaxy hosting the QSO UM287 (a). z=2.3.

Fluorescence of Lya photons originally emitted by the QSO (a)



Cantalupo+14

Summary: take-home messsage(s)

1.- **Disk galaxies are open systems** (if isolated from the environment in a Gyr become red and dead)

2.- (A significant part of) the star-formation at all redshift is driven by gas accretion from the cosmic web.

(Most of) the gas processed in every starburst observed in every galaxy comes directly from the cosmic web

3.- We have a good theoretical understanding of the **cosmic web gas**, however, the **observational characterization** of this central ingredient is in its infancy

Flammarion woodcut